



ISS2011

Conceptual design of MgB_2 coil for the 100 MJ SMES of advanced superconducting power conditioning system (ASPCS)

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Abstract

In order to reduce global carbon-dioxide in the world, we propose an Advanced Superconducting Power Conditioning System (ASPCS) which is composed of 5 MW renewable energy resources and 1 MW hybrid storage system. The hybrid storage system is composed of FC- H_2 -EL and SMES which is installed adjacent to a LH_2 station for vehicles. Since the SMES can be operated at 20 K which is a saturated temperature of LH_2 , we can use MgB_2 superconductors. In the ASPCS, 100 MJ storage capacities of the SMES should be required. This paper focuses on studies into a conceptual design of SMES toroidal coil composed of the MgB_2 and indirectly cooled by LH_2 .

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Keywords: ASPCS; SMES; MgB_2 ; Toroidal coil; LH_2

1. Introduction

It is an urgent issue to reduce global carbon-dioxide in the world, and hence the renewable energy, that is environmentally friendly, should be supplied as a large amount of the electric power. Since installation of a large amount of the fluctuating renewable energy, such as wind turbine (WT) and photovoltaic (PV), will cause the power utility network unstable, we propose an advanced superconducting power conditioning system (ASPCS) that is composed of 5 MW renewable energy resources and 1 MW hybrid storage system [1], [2]. The hybrid storage system is composed of Fuel cell - H_2 -Electrolyzer (FC- H_2 -EL) and superconducting magnetic energy storage (SMES) devices and installed adjacent to a liquid hydrogen (LH_2) station for vehicles. It is reported in Japan that the LH_2 stations have economical merit and environmentally CO_2 reduction if 3,500 stations might be installed by 2030 [3]. The ASPCS has a function of compensating the fluctuating renewable energy with the SMES that has quick response and large I/O power, and with the FC- H_2 -EL that has moderate response and large capacity. We can use MgB_2 superconductors, which has the critical temperature of 39 K [4], because it is indirectly cooled by LH_2 through a thermo-siphon cooling

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pipe. Since the cost of the MgB_2 superconductor is reasonable compared to high temperature superconductors (HTS), we can use a considerable amount of superconducting strand for the large coils. The requirement of the SMES storage capacity is around 50 to 100 MJ by consideration of a trend prediction time [1], [2]. In this study, we carry out a conceptual design of SMES toroidal coil of 100 MJ.

2. Specifications of MgB_2 strand and coil

In consideration of the J_c - B characteristics of the MgB_2 superconductor at 20 K which is a saturated temperature of LH_2 , the maximum acceptable magnetic field is limited to 2.5 T. In this design study, the maximum magnetic field, B_m , is fixed to 2 T. MgB_2 strand manufactured by Hyper Tech Corporation is used for the conceptual design. It has 0.84 mm in diameter and consists of 18 superconducting multifilament and a copper filament. The critical current density at 20 K, 2 T is $J_c=1,100 \text{ A/mm}^2$ and $J_c=200 \text{ A/mm}^2$ [5].

Toroidal configuration is selected for the coil design to reduce leakage magnetic field of the coil. For the toroid, an aspect ratio, a_t , is defined as a ratio of minor radius, r_{in} , to major radius, R_c . The quantity of superconductor, IM in Ampere Meter, is one of the most economically element of the coil and is expressed in terms of the stored energy, the maximum magnetic field and aspect ratio [6].

$$IM = \left(\frac{16\pi^2}{\mu_0} \frac{a_t^3}{(1-a_t)(1-\sqrt{1-a_t^2})^2} \right)^{1/3} \left(\frac{E^2}{B_m} \right)^{1/3} \quad (1)$$

where μ_0 is vacuum permeability, E is the stored energy. Since the stored energy and the maximum magnetic field of the coil are fixed to 100 MJ and 2 T respectively, the Ampere Meter is a function of the aspect ratio. The minimum Ampere Meter value is obtained at $a_t=0.6$, and hence the specifications of the toroidal coil are as follows; $R_c=3.68 \text{ m}$, $r_{in}=2.21 \text{ m}$ and $IM=204 \times 10^6 \text{ A}\cdot\text{m}$.

3. Design of multi strand conductor

The coil is made by the MgB_2 strands, indirectly cooled at 20 K using LH_2 and operated at constant power. Since large current, high strength and high thermal conductivity are required for the conductor, we propose a Cable-in-Conduit (CIC) conductor composed of multi strands. The CIC conductor is designed under the following conditions:

- Maximum conductor stress does not exceed an allowable conductor stress. Since the electromagnetic force in the superconducting coil is large, it is necessary to consider the conductor stress to suppress the coil deformation. The CIC conductor is composite materials based on superconducting filaments, barrier layer, stabilizing layer and reinforcement, and hence the allowable conductor stress can be approximately determined to area ratio and strength of each material.
- CIC conductor stability margin exceeds 1 J/cc. Since the coil is indirectly cooled at 20 K, even if the conductor temperature is increased by disturbance, there is no heat generation in the superconductor until a current sharing temperature. Therefore, the stability margin of the CIC conductor against small perturbations is determined by an enthalpy from an operating temperature to the current sharing temperature.
- Maximum allowable temperature of the superconductor is fixed to 130 K and maximum allowable voltage of the coil is fixed to 2 kV. Since a temperature rise in a quenching CIC conductor leads to potential for degradation of the superconductor, a protective resistance is connected in parallel to the coil. The large stresses caused by the sudden differential thermal expansion may force the conductor to adopt a temperature upper limit. Since the 130 K is often taken as a working limit for the typical winding, we apply it to the proposed CIC conductor. As a worse case, we assume that normal zone heat conduction of the CIC conductor is essentially adiabatic during a quench.

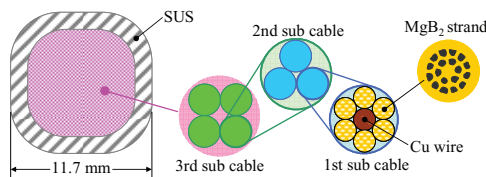


Fig. 1. Composition of CIC conductor.

Table 1. Operating condition and parameters of CIC conductor.

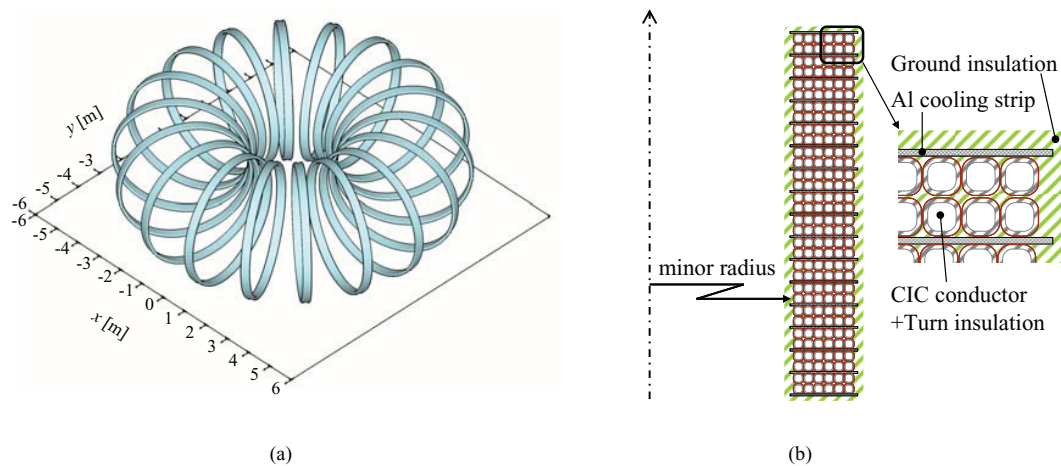
Conductor	CIC	Number of strand	(6SC+1Cu)×3×4
Constant output power	1 MW	Void fraction	0.35
Operating temperature	20 K	Maximum voltage	2 kV
Operating current	4 kA	Size of CIC conductor	11.7×11.7 mm ²
Critical current	8 kA @ 3.98 T, 20 K	Stability margin	1.128 J/cc

Schematic CIC conductor is shown in Fig. 1. Operating condition of SMES coil and design parameters of CIC conductor are shown in Table 1. The proposed CIC conductor is composed of 72 MgB₂ strands and a copper wire placed in a center at 1st sub cable to protect the quenching conductor from overheating. The stranded wire is inserted in SUS conduit 1.6 mm thick. The conductor size is 11.7 mm × 11.7 mm square.

4. Composition of toroidal coil

Toroidal configuration has a merit of smaller leakage magnetic field. Unit coil is made of several double-pancake coils wound with insulated CIC conductor and is inserted with aluminum strip between double-pancakes for heat conduction. The toroidal configuration is composed of a number of the unit coils. Schematic diagram of the toroidal coil composed of 18 unit coils and the cross section of unit coil are shown in Fig. 2. The design parameters of the coil are shown in Table 2.

The unit coil is composed of 16 double-pancake coils, and hence the calculated total number of turns is 3,456. By the mutual coupling of each coil in case of the toroidal coil composed of 18 unit coils, each coil is directed to the center of the coil configuration by the force of 30 MN. The coil has to be strengthened against the centering force. The estimated distance from the center point to 5 gauss line is 8.25 m. The leakage magnetic field is reduced by the toroidal configuration.

**Fig. 2.** Schematic diagram;(a) toroidal coil; (b) cross section of unit coil**Table 2.** Parameters of toroidal coil.

Configuration	Toroid	Number of unit coils	18
Maximum stored energy	100 MJ	Major radius	3.68 m
Maximum magnetic field	2.0 T	Minor radius	2.21 m
Inductance	12.6 H	Unit coil width	0.41 m
Number of turns per unit coil (SP coil×layer)	192 (32×6)	Centering force	30 MN
CIC conductor length	48.7 km	Distance from center point to 5 gauss line	8.25 m

However, the dimension of the coil and the total length of superconductor are $11.9 \times 11.9 \times 4.6 \text{ m}^3$ and 3,506 km respectively which are larger and longer than low temperature superconducting coil due to the low J_c - B characteristics of the MgB_2 superconductor. It is estimated that the MgB_2 engineering current density, J_e , at 20 K will be improved from 200 A/mm² at 2 T to 200 A/mm² at 5 T in a few years [5], [7]. If the MgB_2 strand is improved, we can use a higher magnetic field, and hence can redesign compact and economical coil because the major radius is proportional to $B_m^{-2/3}$ and the Ampere Meter is proportional to $B_m^{-1/3}$ [6].

5. Analysis of AC loss for ASPCS

The SMES coil is exposed by changing magnetic field at compensation of fluctuating power generation and then heated by AC loss. Since a MgB_2 filament and a strand are surrounded by barrier layer and high resistance layer respectively, the AC loss is dominated by hysteresis loss of each MgB_2 filament. The hysteresis loss of the coil for a typical WT power waveform during 20 hours is estimated. The WT power waveform includes the wind power, wind trend power and SMES I/O power. The SMES coil has to be operated at the output power of 1 MW in the whole range from the minimum stored energy of 20 MJ to 100 MJ. If an available energy of the SMES is 80% of the maximum stored energy, a standby current becomes 3.1 kA. The estimated hysteresis losses are as follows; an average value is around 9.3 W, a maximum value is around 66 W and a total value during 20 hours is 0.67 MJ. In the worst case, a maximum hysteresis loss per unit length of the CIC conductor is estimated at around 2.5 mW/m.

6. Conclusion

We propose the advanced superconducting power conditioning system (ASPCS) to compensate the fluctuations of the renewable energy resources such as WT and PV. The 100 MJ SMES coil is one of the key component of the system. The coil assembled in the toroidal configuration is composed of unit coils fabricated with MgB_2 superconductor, and the coil is indirectly cooled by LH_2 . The conceptual design study is performed to check conductor stability, coil protection, leakage magnetic field, AC loss by the compensation and so on.

In order to make the 100 MJ SMES toroidal coil into practical use, the most important subject is to develop high performance MgB_2 superconductor. Although the maximum magnetic field is fixed to 2 T in this study, it is expected to increase it up to around 5 T for more compact and economical coil.

Acknowledgements

This research was supported in part by the JST-ALCA in Japan.

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